REVIEW

Indian J. Phys. **67B** (2), 109-131 (1993)

Nucleosynthesis involving mainly neutron capture processes

Ramen Kumar Parui
Department of Physics, Manipur University, Canchipur, Imphal–795 003, India

Received 25 October 1991, accepted 13 January 1993

Abstract : Neutron star is one of the possible endpoints of stellar evolution. High mass stars become neutron stars after suffering a supernovae explosion. In this paper, I have discussed various neutron producing reactions (*i.e.* neutron sources) in nucleosynthesis during different evolving stages *i.e.* main sequence stage, red giant stage, supernova stage and neutron star stage; neutrons produced in one stage come into the next stage as remnant and play an active role to begin nucleosynthesis in the next stage, and ultimately the formation of a neutron star.

Keywords : Nucleosynthesis, supernova remnants, neutron star.

PACS Nos. : 95.30.Cq, 98.40.Ne, 97.60.Jd; 67.90.+z

Plan of Articles

1. Introduction

Star formation is believed to take place preferably where the interstellar matter is compressed. If the radius of a spherical mass of gas is forced to decrease under a critical value computed by Jeans, it becomes unstable, collapses, and leads to a protostar. When the radius of the protostar is not too large ($R \simeq 10^5 R_\odot$), the density is 10^{-15} g.cm^{-3} the collapse is rather rapid. Then the pressure forces inside the protostar begin to brake the gravitational collapse. The star goes on contracting in a thermostatic time (~ 10^7 years). When the temperature and the density at the centre become high enough, the nuclear burning takes place. The idea that nuclear reactions were occurring among light nuclei in stellar interior had been known for some time [1,2]. The discovery of Technetium (Tc) in stars established that heavy nuclei ($A > 65$) were undergoing nuclear reactions as well [3–9].

The earlier theories of nucleosynthesis attributed to the phenomenon of absorption of neutrons by lighter elements, the existence of all the elements heavier than hydrogen. According to these theories, the production of the lighter elements ($1 < A \leq 40$) was attributed to the capture reactions between charged particles; and the production of the heavier elements $40<A<65$, to the photodisintegration and recombination reaction in statistical equilibrium. The heavy elements ($A > 65$), because of their high charge and the relatively less stability, can be explained by neither of these two processes. But the detailed study of the chain of nuclear reactions which take place during stellar evolution shows that at certain times, large neutron fluxes are released in the core of the star. On the other hand, the analysis of the relative abundance of the elements formed in this way shows certain regularities which can only be explained in terms of neutron absorption [10–14]. So it is useful to obtain a method for calibrating the neutron sources, in order to be able to evaluate their relative importance in nucleosynthesis.

High mass stars became neutron stars or blackholes after having exploded at their supernovae stages. The constituents of neutron stars are strictly related to their past history *i.e.* their relation with the main sequence phase, red giant phase, and supernovae explosion where they presumably originated. The details of how a star behaves after its red giant stage through main sequence stages are not yet fully understood. However, we know more about the final stage itself than about how the transition to this stage occurs. The final state here means the state when a star has exhausted all its nuclear fuels *i.e.* it can no longer draw on thermonuclear reactions to supply the energy and the pressure needed to withstand gravitation. When a massive star has reached the end of its nuclear fuel, it can become a 'supernova'. A supernova arises when the core of a star collapses under its own gravitational contraction, releasing energy which causes the outer envelope to explode *i.e.* the inner part of the star undergoes an implosion while the outer part of the star undergoes an explosion. The imploding core of supernova II may form a neutron star. In this paper, attempts have been made to present the possible neutron producing sources in each evolving pre-neutron star stage *i.e.* how neutrons are produced in nucleosynthesis in main sequence, red giant phase, supernovae stage and neutron star stage. Neutrons produced in one stage come into next stage as remnant and play an active role to begin nucleosynthesis in the next stage, ultimately leading to the formation of neutron star.

2. Star formation

It is believed from observational evidences that stars form by contraction of interstellar clouds of gas and dust found in Galaxies. Typical densities in such regions are around 10^{-19} Kg.m^{-3} (*i.e.* about 10^8 hydrogen atom per cubic meter), and infact, such clouds are predominantly made of neutral hydrogen. The temperature of these regions are about 100°K. But a cloud of gas large enough to contain so much matter will not have a gravitational field strong enough to induce contraction. From Jeans condition, we know that a necessary but not sufficient condition for contraction is that gravitational force overcomes the elastic force of gas. This gives, for interstellar matter with temperature $T \sim 100$°K, the density $\rho = 2.5 \times 10^{-19}$ g.cm^{-3} for 1 solar mass. For simplifying the case consider the contraction of a sphere of one solar mass.

At the beginning, such an object is transparent to its own radiation field. Dust grains in interstellar space are very effective in radiating away heat. Whenever a hydrogen atom collides with a dust grain, the grain becomes slightly heated, and this energy is radiated away *i.e.* thermal radiative emission takes place. The energy that is radiated away by the grains reduces the kinetic energy of the gas because it is this energy that is transferred to the grains in the collision of atoms with dust. When the gas loses kinetic energy, it falls towards the center of the cloud through gravitational attraction, gains some kinetic energy in falling, and again transfers some of this to a dust grain to repeat the cooling cycle. The atom transfers some of its centrally directed momentum to the grain thus also causing the grains to drift in towards the center of the contracting cloud. As a result of many such interactions, the cloud as a whole contracts. The contraction produces a core of uniform density, and an envelope where the density runs almost as r^{-2}. When the central density is about 10^{-13} g.cm^{-3}, an opaeque core (first.core) develops, in which the central temperature goes up. When the temperature at the centre has increased, a small central core (second core) appears, which is almost in hydrostatic equilibrium *i.e.* in balance between the pressure force and the gravitational force, while matter is still falling in from outside ($m \sim 10^{31}$ gm, $R \sim 6 \times 10^{13}$ cm, $\rho \sim 2 \times 10^{-10}$ g·cm^{-3}, $T \sim 170$°K). In these initial stages the force of gravitation between different constituents of the objects is so strong as to cause a rapid collapse of the object as a whole. But this does not occur smoothly. It is rather catastrophic, generating shockwaves throughout the star. Heat is generated, owing to the compression. As a result, a strong internal pressure builds up in the star, which tends to slowdown the compression—until the object settles down to a more or less static state in which state the pressure forces are in balance with the gravitational force. A further increase in temperature leads to the dissociation of H_2 and dynamical instability. Further collapse takes place ($m \sim 3 \times 10^{30}$ gm, $R \sim 9 \times 10^{10}$ cm. $\rho \sim 2 \times 10^{-2}$ g·cm^{-3}, $T \sim 2 \times 10^4$). The core then expands until it can radiate away, and contracts again, and finally accretes matter until it becomes a star.

When a star first forms from the interstellar medium it contracts, radiating away gravitational energy. As the star contracts gradually the heat energy is transported from its interior to the outer regions of the star and it develops a radiative core. When the temperature at the centre of the star becomes about a million degrees, the first nuclear reaction sets in.

Various nuclear reactions take place in stars. Most of the reactions are those, in which two particles approach to within a short distance, become bound to each other, and at the same time release energy. The average thermal energy inside a star goes from a few KeV upto a few hundreds of KeV while the Coulomb barrier is at least a few MeV for all the interacting nuclei. So a nucleus inside the star, on the average, does not have enough energy to overtake the Coulomb repulsion. Due to a quantum effect called tunnel effect, a less energetic nucleus can overcome the Coulomb repulsion and it has a chance to be close enough to the target to interact with it. This is the only way for a nuclear reaction to occur at low energies.

3. Abundances

3.1. Abundances :

The success of the nucleosynthesis depends on the atomic abundance pattern observed in nature. Enormous efforts have been invested to determine the abundances. The present knowledge of abundances has been established essentially during the past six decades. It was based on the hypothesis that primitive meteorites might have preserved the original compositions of the early solar system [15]. In 1928 Russel and Adams [16] first gave some idea on solar abundances. Fifteen years ago, the first quantitative abundance determinations were made from solar spectra [17]. On an average, the analyses of stellar spectra yield surprisingly good agreement with solar values. This generalisation of solar abundances led to the idea of "Cosmic abundances", assuming a homogeneous abundance distribution throughout our galaxy with the solar system being a representative sample. This homogeneity was considered to support the hypothesis of a cosmic event which created all matters in the Universe and also that these element-abundances have changed only marginally afterwards, by stellar nuclear burning.

However, present improvements in observation techniques led to the observation directly of the abundance pattern in objects like red giants, supernova remnants, interstellar matter etc [18], which are now considered as direct clues to stellar nucleosynthesis.

In successive stages of stellar evolution, a sequence of burning processes converts H to He, He to C, and so on until the isotopes around iron are reached. These are the most stable nuclei in nature, exhibiting the highest binding energy per nucleon, and their stability results in a large abundance maximum around $A = 56$. Beyond that point, fusion of charged particles quickly ceases to contribute to the observed abundances because of the increasing Coulomb barriers and the decreasing binding energies per nucleon. Heavier nuclei can only be created by successive neutron capture reactions and beta decay.

In 1948, Alpher [19] first noted the correlation between first neutron capture cross-section and the abundances of heavy elements. This was interpreted in terms of a big bang origin for the heavy elements [20]. But this correlation did not yield good results, for most big bang neutrons simply combine with protons to form ^4He [21-23]. The next advance in ideas on neutron-capture processes in stellar nucleosynthesis was preceded by some important discoveries like strong Tc I line in S-stars [24], observations of generally enhanced heavy element ($A > 75$) abundances in S-stars, Ba II, and Carbon stars [25 - 31], and decay time of ^{254}Cf [32,33]. The essential ideas for stellar neutron capture were outlined by Hoyle *et al* [34], Burbidge *et al* [35] and Cameron [36]. These ideas still form the basis of the contemporary view point. In these early works it was recognised for the first time that the atomic abundances of elements heavier than iron not only require neutron capture to account for their existence, but exhibit abundance peaks which are naturally explained by the nuclear physics aspects of the capture process.

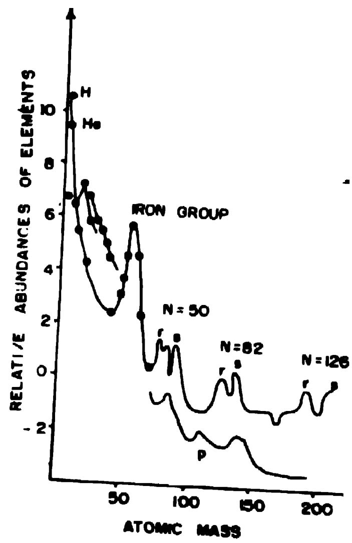

Figure 1. Heavy element abundances (silicon $=10^6$) as a function of atomic mass (see Ref. 37).

Figure 1 is an illustration of the modern abundance curve [37] as a function of atomic mass. The abundances decrease roughly exponentially (except an odd-even effect) with increasing mass number upto $A \sim 100$. The trend then flattens to a stepwise behaviour with notable peaks near $A = 80$, 130, 138, 195 and 208. The decreasing abundances for $A > 70$ suggest the sequential capture of neutrons from initial "seed" iron-like nuclei. The upper peak of the pair corresponds to the neutron closed shells on the line of beta stability. An increase in the abundance of these nuclei can naturally be explained by their decreased neutron capture cross section [35]. This suggests neutron capture timescale which are slow (s–process) compared to the beta decay life times ($1–10^5$ years) of nuclei one neutron removed from stability. The lower peak of the pair can also be attributed to properties of neutron-closed shell nuclei 5–10 neutrons removed from the line of beta stability on the neutron-rich side. This would require neutron capture on a rapid (*r*–process) timescale compared to beta decay rates (~ 1 – 1000 ms). On the other hand, some nuclei having increased proton rather than neutron numbers are said to be produced by a bypassed process called *p*-process. The *p*-process elements are stable but much less abundant than the *s*- and *r*–processes (by a factor ranging from 0.001 to 0.01). In first approximation their abundance curve is parallel to the *s*- and *r*-element curve. In particular, the *p*-process elements with magic number nuclei, are more abundant than their neighbours. These elements can not be synthesized by neutron capture processes.

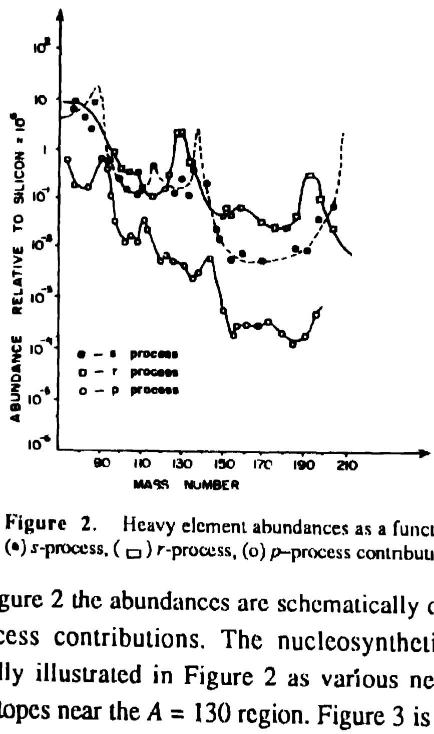

Figure 2. Heavy element abundances as a function of atomic mass approximately divided into (•) *s*-process, (□) *r*-process, (o) *p*–process contribution (see Ref. 38).

In Figure 2 the abundances are schematically decomposed into *s*-process, *r*-process, and *p*–process contributions. The nucleosynthetic processes for heavy nuclei are schematically illustrated in Figure 2 as various neutron capture and beta decay flows through isotopes near the A = 130 region. Figure 3 is a schematic representation of various neutron-capture processes contributing to the abundances of heavy nuclei. *S*-process branching of the neutron-capture chain has been indicated by hatched lines where the rates for beta-decay and neutron-capture are comparable. At ^{63}Ni, ^{79}Se, and ^{85}Kr, competition between neutron-capture and beta-decay leads to a branching of the synthesis path which is determined by the *s*-process neutron density and the respective beta half life.

3.2. Nuetron production site for s-process .

One possibility is the ^{2}H (d, n) ^{3}He reaction during main sequence hydrogen burning. This reaction is, however, suppressed by competing reaction ^{2}H (p, γ) ^{3}He and ^{2}H (d,p) ^{3}H. Furthermore, the ^{3}He (n, p) ^{3}H reaction acts as a neutron 'poison'. These combined effects render this possibility unimportant as a neutron source. The best candidate nuclear reactions are the helium burning reactions ^{13}C (α, n) ^{16}O [39,40] and ^{22}Ne (α, n) ^{25}Mg [41]. The ^{21}Ne (α, n) ^{24}Mg process was originally proposed in ref. [35] as a possibility, but has since been shown to be less effective than ^{13}C and ^{22}Ne.

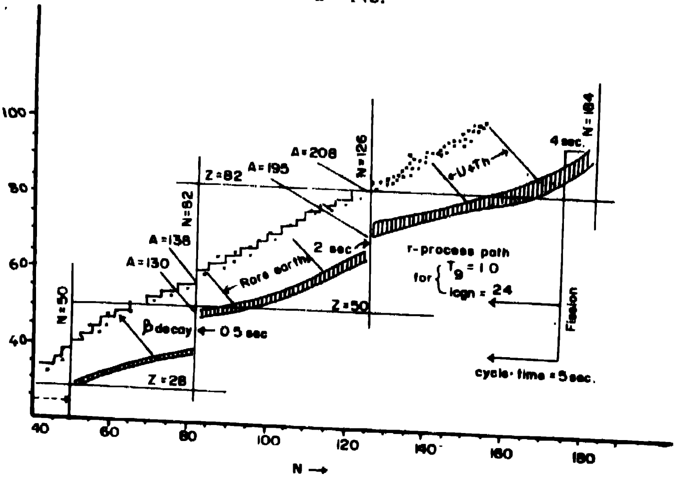

Figure 3. Neutron capture paths for the s-process, and r-process. The r–process follows a path along the line of beta decay stability. The stable r-process nuclei are shown here as small circles and have neutron rich progenitors, the waiting points, which are inside the shaded area. The r–process path is shown here for $T = 10^9$ K and neutron density $n = 10^{24}$ neutrons. cm^{-3}.

Another possibility in the carbon burning ^{12}C (^{12}C, n) ^{23}Mg reaction [41 - 43]. This reaction is capable of producing enough neutron captures per seed [43,44]. One possible problem with this source, however, is that it occurs at a relatively high ($T_8 = T \times 10^8$ °K) temperature. The thermally enhanced beta decay rates associated with such temperature may lead to s–process branching which is not consistent with the observed value. The oxygen burning ^{16}O (^{16}O, n) ^{31}S reaction would have the same problems. Of the possible stellar environments for the s-process, the He burning reactions are the most suitable.

3.3. Neutron production site for r-process :

The site for the r-process has remained an unsolved puzzle. The occurrence of a distinct abundance peak in Figure 2 clearly indicates that such a high neutron-flux-environment must have occurred somewhere. The sharpness of the peaks indicates that a relatively narrow range of environments have contributed to this process.

Burbidge *et al* first suggested that the r-process occurred in the outer envelope of supernova cores. Other possible sites are neutronised cores of exploding supernovae [45], shock induced explosive helium burning in supernova [35,46 - 49]. Another possibility, for type II supernovae, is in lower mass stars ($8\ M_\odot \leq M \leq 10\ M_\odot$) [50-52]. The other likely site for the r-process is in the outer envelopes of type II supernovae. As the shock traverses the helium burning shell, explosive thermo nuclear buring could lead to extensive neutron production via the ^{22}Ne (α, n) ^{25}Mg or the ^{13}C (α, n) ^{16}O reactions [53-55]. A similar r-process may occur as the shock wave traverses the C/Ne shell [56].

4. Main sequence and red giant phase

The abundance of elements leads to a series of stellar nucleosynthetic processes [35, 57] as follows :

a) Hydrogen burning (conversion of hydrogen into helium)
   Temperature $T > 10^7$K
   Duration $\approx 10^{10}$ years

b) Helium burning (conversion of helium into carbon, oxygen, etc)
   Temperature $T \geq 10^8$K
   Duration $\approx 10^7$ years

c) Carbon burning, oxygen burning (production of $16 \leq A \leq 28$)
   Temperature $T \geq 6 \times 10^8$K for carbon burning
   Temperature $T \geq 10^9$K for oxygen burning
   Duration $\approx 10^5$ years unless nucleosynthesis is explosive

d) Silicon burning (production of $28 \leq A \leq 60$)
   Temperature $T > 3$ or 4×10^9K
   Duration for the quasiequilibrium and '*e*' process $\approx$ 1 sec

e) The *s*-process (production of $A \geq 60$)
   Temperature $T > 10^8$K
   Duration $\approx 10^3$ to 10^7 years

f) The *p*-process (production of the low abundance proton rich heavy nuclei)
   Temperature $T > 2$ or 3×10^2K
   Duration $\approx$ 10 – 100 seconds

g) The *r*-process (production of $A \geq 60$)
   Temperature $T > 10^{10}$ K
   Duration $\approx$ 10-100 Seconds (uncertain)

4.1. *Pre-hydrogen burning phase :*

The deuterium present in the contracting stellar gas burns when temperature is $\sim 10^6$K. The relative abundance of deuterium at that time is very small (*i.e.* $< 10^{-4}$) compared with that of the hydrogen. The deuterium is destroyed by the $D\,(p,\gamma)\,^3$He, $D(D,n)\,^3$He and $D\,(d,p)\,^3$H reactions. 0.1 neutron per initial deuteron is produced from these reactions (*i.e.* 10^{-5}n per hydrogen atom). The presence of ^{3}H reduces further the number of neutrons available for the synthesis of heavy elements through the reaction ^{3}He$(n,p)^3$H. So the contribution of the deuterium towards the synthesis of heavy elements can be neglected [58].

4.2. *Hydrogen burning phase :*

The element synthesis begins with the primeval hydrogen condensed in the stars with (p,p) chain reaction. In this process both (p,p) and (C–N–O) cycles occur but no neutron is available as the product. When the star first contracts, the generation of energy by hydrogen burning develops internal pressure which opposes gravitational contraction, and the star is stabilized on the main sequence at the point appropriate to its mass.

4.3. Helium burning phase :

When hydrogen burning in a star's main sequence stage leads eventually to hydrogen exhaustion, a helium core remains at the star's centre. Then the contraction phase proceeds to helium burning. Salpeter [59,60] and Opik [61,62] suggested that the fusion of helium plays an important role in energy generation in and element synthesis in the red giant stage of the star's evolution. The reactions are assigned to the triple alpha process :

$$^{4}He + {}^{4}He \rightleftarrows {}^{8}Be$$

$$^{8}Be + {}^{4}He \rightarrow {}^{12}C + \gamma$$

or $$3\,^{4}He \longrightarrow {}^{12}C + \gamma + 7.274 \text{ MeV}$$

Hoyle and Schwarzschild [63] suggested that these processes occur at a late stage of the red giant evolution in which the hydrogen in the central core has been largely converted into helium and in which gravitational contraction has raised the central temperature to 10^{8}K. Even though very small the equilibrium concentration of ^{8}Be is sufficient to lead to considerable production of ^{12}C through radiative alpha particle capture by the ^{8}Be, and of ^{16}O, ^{20}Ne, etc by succeeding alpha particle captures.

It is believed that helium burning results in the production of approximately equal amounts of ^{12}C and ^{16}O in stars in the wide range of masses from 0.5 M. — 50 M. Once ^{12}C is formed, alpha capture process will become active and the reaction products of C–N–O cycle might also produce neutrons [64,65,66] and von Weizsacker [67] predicted that when ^{13}C produced in helium burning is mixed with hydrogen at high enough temperature, hydrogen is converted to ^{4}He by the C–N cycle which in addition produces ^{13}C. The reaction is

$$^{12}C\,(p, \gamma)\,^{13}N\,(\beta^{+}, \upsilon_{+})\,^{13}C$$

That the ^{13}C formed in the C–N–O cycle can act as a source of neutrons as well as other particles was proposed by Greenstein. [68], Cameron [69] and Fowler *et al* [70], Lang [71] and Audouze and Vonclair [72].

$$^{13}C + {}^{4}He \qquad {}^{16}O + n + 2.214 \text{ MeV}$$

$$^{14}N + {}^{4}He \qquad {}^{18}F + \gamma + 4.416 \text{ MeV}$$

$$^{18}F \qquad \longrightarrow {}^{18}O + e^{+} + \nu_{e}$$

$$^{18}O + {}^{4}He \qquad \longrightarrow {}^{21}Ne + n - 0.699 \text{ MeV}$$

$$^{18}O + {}^{4}He \qquad \longrightarrow {}^{22}Ne + \gamma + 9.667 \text{ MeV}$$

$$^{21}Ne + {}^{4}He \qquad \longrightarrow {}^{24}Mg + n + 2.58 \text{ MeV}$$

$$^{22}Ne + {}^{4}He \qquad \longrightarrow {}^{25}Mg + n - 0.481 \text{ MeV}$$

$$^{22}Ne + {}^{4}He \qquad Mg + \gamma$$

$$^{25}Mg + {}^{4}He \longrightarrow {}^{28}Si + n$$
$$^{26}Mg + {}^{4}He \qquad {}^{29}Si + n$$

and special case

$$^{29}Si + {}^{4}He \longrightarrow {}^{32}S + n - 1.53 \text{ MeV}$$
$$^{33}S + {}^{4}He \longrightarrow {}^{36}A + n - 2.0 \text{ Mev}$$

Thus, we see that heavy elements with mass numbers $A > 65$ are synthesized in red giant stars by the slow neutron capture process (s–process) and the neutrons required for this mechanism are provided by (α, n) reactions in the helium burning shell of the star. Concerning the alpha-capture process, ^{13}C and ^{22}Ne take part in major reactions while very little ^{17}O remains for helium burning. Cameron [39, 69] and Greenstein [68] emphasized that exothermic reaction ^{13}C (α, n) was the neutron source. The essential difficulty lies in the the fact that only a small amount of ^{13}C is produced at equilibrium in the C-N cycle; $^{13}C/^{12}C = 1/4.6$ by number at equilibrium. As a result few neutrons are produced when ^{13}C begins to interact with the helium. The Cosmic abundance ratio $^{12}C / {}^{56}Fe = 6.4$ implies that $6.4/4.6 = 1.4$ neutrons will become available per iron nucleus and these will only be sufficient to build nuclei slightly heavier than ^{56}Fe. But difficulties arise from the fact that ^{14}N is the most abundant of the isotopes at equilibrium in the C–N cycle. The reaction ^{14}N (n,p) ^{14}C consumes a large fraction of the neutrons produced in the ^{13}C (α,n) ^{16}O reaction. To avoid these difficulties Cameron emphasized that the ^{13}C (α, n) ^{16}O reaction is the neutron source, if it is postulated that considerable mixing between core and envelope takes place during the giant stage. Then hydrogen from the envelope interacts with ^{12}C produced in the core ($3\,{}^{4}He \rightarrow {}^{12}C$) and maintains constant supply of ^{13}C at such a rate that little ^{14}N is produced by the ^{13}C (p, γ) ^{14}N reaction. It may also be mentioned that if ^{12}C is mixed with the cooler outer regions of the core, where ^{13}C is burning, then ^{12}C capture the protons produced from the reaction ^{14}N (n, p) and replenishes the ^{13}C. This permits all neutrons produced to be used for the synthesis of heavy elements just beyond ^{56}Fe.

But Fowler [70] proposed another reaction as an alternative source of neutrons. The reaction is ^{21}Ne (α, n) ^{24}Mg. According to their proposed method, ^{20}Ne produced in the helium burning stage, is converted into ^{21}Ne in the hydrogen burning shell at about 30 – 50 $\times 10^{6}$K surrounding the helium burning cores of red giant stars. The ^{21}Ne then interacts with helium to produce neutrons which are captured by iron group nuclei to produce heavy elements. Of course, these reactions will have to satisfy some conditions, such as the production of ^{21}Ne from the reaction ^{20}Ne (p, γ) ^{21}Na (β^{+}, ν_{+}) ^{21}Ne is faster than the production of ^{22}Na from the reaction ^{21}Ne (p, γ) ^{22}Na; the consumption of ^{21}Ne by ^{21}Ne (α,n) ^{24}Mg reaction before helium is depleted in the core, etc. In general

i) ^{21}Ne is indeed produced from ^{20}Ne faster than it is destroyed.

ii) The conversion of ^{20}Ne into ^{21}Ne will not occur before the hydrogen is exhausted by the C–N cycle or oxygen reaction unless there is only a small concentration of carbon, nitrogen and oxygen.

iii) ^{14}N will be fairly well scourced out at low temperatures before ^{21}Ne begins to interact.

iv) When the concentration by weight of helium < 0.1, the ^{21}Ne will be consumed. Thus we see that with the consumption of ^{13}C in its central region, the core now heats to greater temperatures and rapidly processes ^4He by 3 $^4He \longrightarrow {}^{12}C$. Towards the end of helium burning, instability may well set in and mixing may occur throughout the core and with the envelope hydrogen. New ^{13}C is produced, ^{21}Ne burns, and a great flux of neutrons is produced.

But Ulrich [73] and Iben [74] suggested that the reaction ^{13}C (α, n) ^{16}O and ^{22}Ne (α, n) ^{25}Mg are the most important neutron sources for the astrophysical *s*–process. Recent measurements on both reactions in the energy region of helium burning shell and stellar reaction rate suggest that the most favourite neutron source for the *s*-process is the reaction ^{22}Ne (α, n) ^{25}Mg, for this reaction has a negative Q value of Q = –0.482 MeV [75]. The reaction rate ^{22}Ne (α, n) ^{25}Mg has been first evaluated by Caughlan *et al* (CFHZ) [76], using experimental data above the laboratory energies E_α = 1.9 MeV and nuclear systematics at lower energies. But the reaction rate has suffered several changes in the last years. The ^{22}Ne (α, n) reaction is considered as one of the primary neutron sources for the

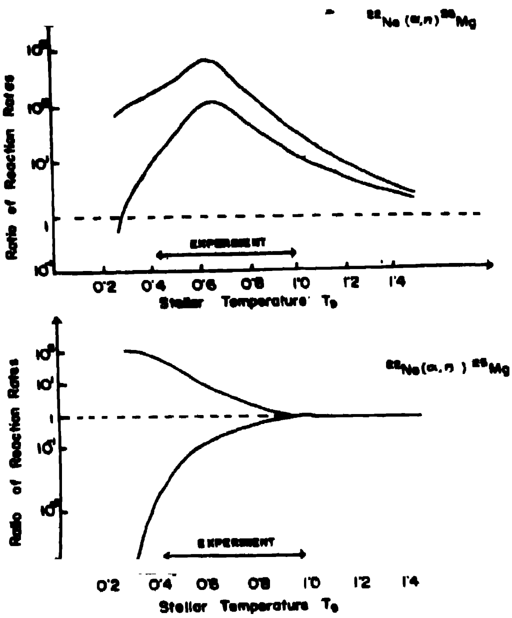

Figure 4. Comparison of experimentally confirmed stellar reaction rates to CFHZ (ref. 76) compilation, for reaction ^{22}Ne (α, γ) ^{26}Mg(above) and ^{22}Ne(α, n) ^{25}Mg (below). The curves show the experimentally confirmed lower and upper (estimates base on ^{22}Ne(n, γ) ^{26}Mg information included) limits of the ratio (see Ref. 75).

nucleosynthesis of heavy elements, but at the same time ^{22}Ne is also effective as a neutron poison via the ^{22}Ne (n, γ) react in. Therefore, neutron capture cross section is of essential importance in the assessment of the neutron balance [77 – 79]. So a quantitative discussion of the stellar reaction rates $< \sigma v >$ of these reactions at temperatures of the helium burning shell ($T_9 = 0.4 \rightarrow 1.0$; T_9 means $T \times 10^9$ °K) measured in various experiments is given below:

Figure 4 shows the experimental results obtained by Wolke *et al* [75]. The reaction rate of ^{22}Ne (α, γ) ^{26}Mg is mainly dominated by the contribution of resonance at $E_\alpha = 0.830$ MeV. A comparison of their results with the CFHZ [76] compilation, which is not based on the spectroscopic data, reveals that the experimentally confirmed lower limit of $<\sigma v>$ is up to a factor of 100 larger than assumed before. For the ^{22}Ne (α, n) ^{25}Mg reaction we have no unambigious result. The ratio of the rates of the two competing reactions ^{22}Ne (α, n) ^{25}Mg and ^{22}Ne (α, γ) ^{26}Mg as a function of temperatures is shown in Figure 5. Their results reveal a value at $T_9 = 0.6$°k which is at least a factor of 30 smaller than CFHZ compilation.

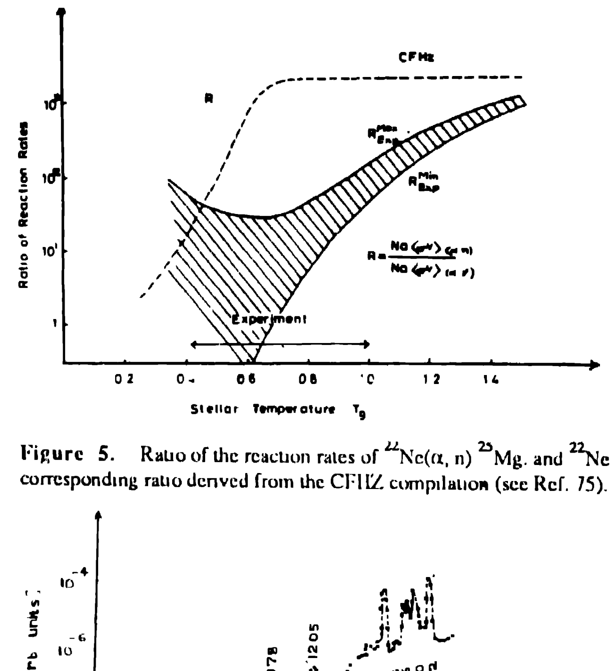

Figure 5. Ratio of the reaction rates of ^{22}Ne(α, n) ^{25}Mg. and ^{22}Ne (α, γ) ^{26}Mg compared to the corresponding ratio derived from the CFHZ compilation (see Ref. 75).

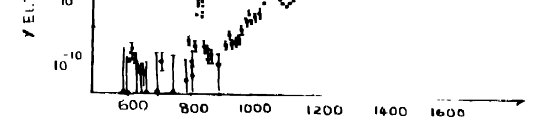

Figure 6. Excitation function of ^{22}Ne (α, n) ^{25}Mg. All points are taken with a 13 KeV thick target except where indicated. The resonances are lebelled by their laboratory energies.

Thus, the neutron production will be less efficient than what was assumed before. But because of the large error bars in the calculations of the reaction rates at low temperatures due to uncertainties in the low energy cross section, the authors suggest that additional experimental data are required especially on low energy (α, n) cross section. So, the reaction rate of ^{22}Ne (α, n) ^{25}Mg is affected by very large uncertainties in the low temperature regime for He burning conditions below $T_9 \approx 0.35$°k.

In spite of the importance of the ^{22}Ne (n, γ) reaction, the knowledge of its cross section is very unsatisfactory [79]. To improve the situation, a ^{22}Ne (n, γ) measurement was performed using activation techniques.

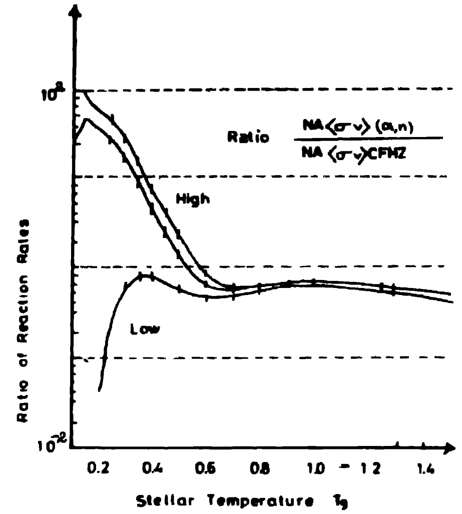

Figure 7. Stellar reaction rates of ^{22}Ne (α, n) ^{25}Mg from present work and compilation (CFHZ), where for a better comparison only the ratio of the two rates are plotted. The level 'high' and 'low' represent uncertainties by taking into account the upper limits from unobserved low resonances [83, 85].

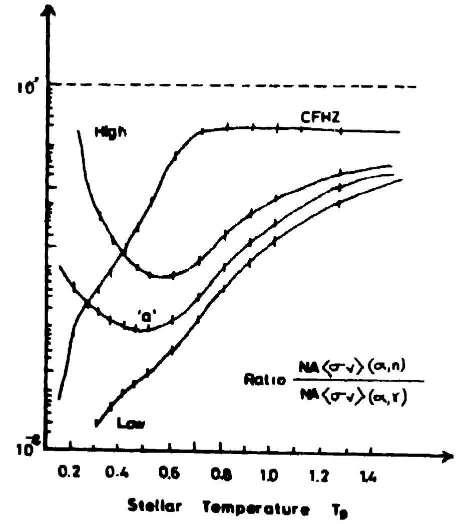

Figure 8. Ratio of reaction rates of ^{22}Ne (α, n) ^{25}Mg and ^{22}Ne (α, γ) ^{26}Mg reaction as a function of stellar temperature T_9. The curve marked by 'CFHZ' gives the values of the compilation. The curve with label 'a' shows the results of Drotleff *et al* [80], considering the contributions of all resonances with $E_\alpha < 2.05$.

Recent investigations by Drotleff *et al* [80] and Descouvemont [81] show that the $^{13}C(\alpha, n)\ ^{16}O$ as well as $^{22}Ne\ (\alpha, n)\ ^{25}Mg$ is a possible neutron source for the nucleosynthesis in the *s*-process. In their experiment, they obtained the excitation function of $^{22}Ne\ (\alpha, n)\ ^{25}Mg$ at E_α = 600 KeV to E_α = 1650 KeV (as shown in Figure 6). The resonance structure observed at E_α > 1 Mev is in good agreement with the previous work (CFHZ). At lower energies, two new resonances are found at E_α = 625 and 842 KeV. These two resonances correspond to ^{26}Mg levels known from (γ, *n*) and (*n*, γ) measurements done by Wolke *et al* [82], and Berman *et al* [83]. The ratio of the (α, *n*) to the (α, γ) reaction rates is given in Figures 7 and 8 in comparison with the CFHZ value. The resonance at E_α = 625 KeV dominates the reaction rate at $0.1 < T_9 < 0.3$ completely, being higher than the CFHZ estimate. At $0.3 < T_9 < 1.5$ the reaction rate is considerably smaller than the CFHZ value, inspite of the new 842 KeV resonance, because of the strong resonance at 828 KeV in the (α, γ) channel, which is not compensated as observed by Descouvemont [81] and shown in Figure 9.

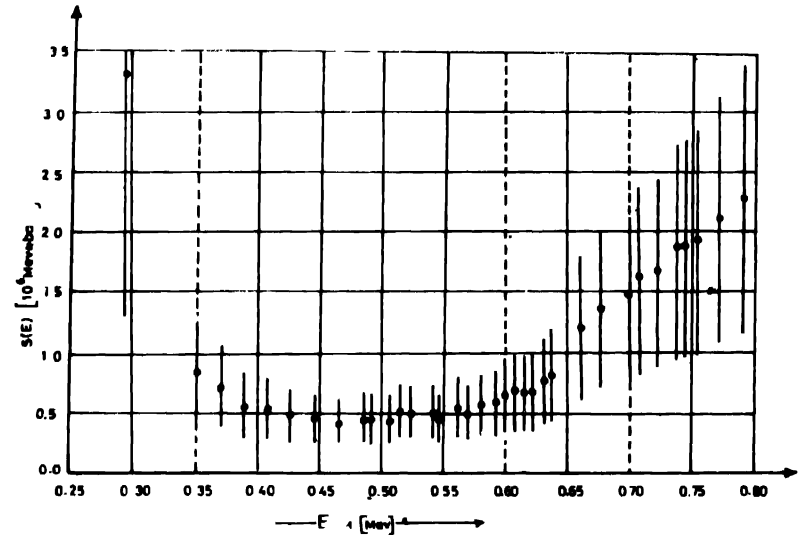

Figure 9. The astrophysical *S* factor the $^{13}C\ (\alpha, n)\ ^{16}O$ reaction increases to lower energies in accordance with [81].

But Raiteri *et al* [84] have argued that for the *s*-process occurring in low mass stars ascending the Asymptotic Giant Branch while suffering thermal pulses, the major neutron source is not the $^{22}Ne\ (\alpha, n)\ ^{25}Mg$ reaction, but the $^{13}C\ (\alpha, n)\ ^{16}O$ one. However, an enhanced (α, *n*) rate leads to an increase of the peak neutron density during the activation of minor ^{22}Ne source.

Recently, Drotleff *et al* [85] have investigated the excitation function of $^{22}Ne\ (\alpha, n)\ ^{25}Mg$ in the range of E_α = 570 KeV to 2100 KeV, and obtained two new resonances at E_α = 623 + 6 and 838 + 6 KeV which are shown in Figure 10. The energy of both new resonances deviated by more than one standard deviation from the energy of ^{26}Mg levels known from (α, n) and (n, γ) measurements [83, 86]. The resonance of 623 KeV could be due to ^{9}Be (α, n) ^{12}C [87,88] or ^{11}B (α, n) ^{14}N [89]. ^{13}C (α, n) ^{16}O has no resonances in this energy range.

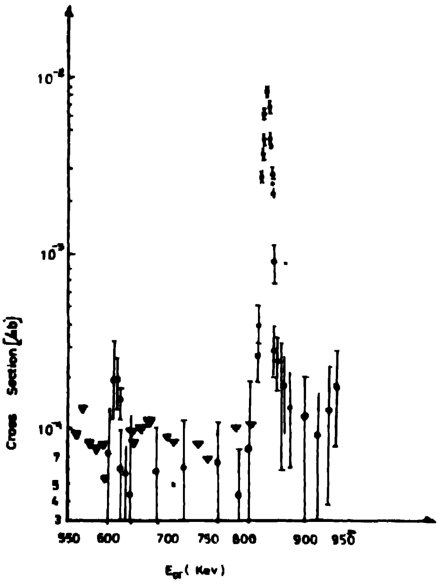

Figure 10. Resonances at 623 ± 6 and 838 ± 6 KeV observed in the reaction ^{22}Ne (α, *n*) ^{25}Mg.

So, if one ascribes the resonance at 623 KeV to ^{22}Ne (α, n) ^{25}Mg reaction, it would dominate the reaction rate completely for $T_9 < 0.3$ leading to a higher rate than CFHZ. So, the origin of the resonance of 623 KeV will need further investigation to know the exact role of ^{22}Ne (α, n) ^{25}Mg.

In the alpha capture process the heavier nuclei are formed by successive fusion with more and more helium nuclei. Thus, we get ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S etc. This successive addition of an alpha particle can not go on indefinitely [64,90,91] because Coulomb repulsion grows stronger as the nuclear charge increases. Beyond silicon or sulphur the process operates in a different manner. When one ^{28}Si disintegrates into seven alpha particles, then they combine with another ^{28}Si to form ^{56}Ni. ^{56}Ni decays into ^{56}Co and then ^{56}Fe. The process terminates when these three nuclei *i.e.* Ni, Co, Fe of the iron group are formed.

4.4. *Carbon and oxygen burning :*

The nuclear ashes of helium burning in massive stars are ^{12}C and ^{16}O, where the relative abundance of these two species is determined by the yet rather unknown ^{12}C (α, γ) ^{16}O reaction. Following helium burning a massive star can ignite carbon and burn hydrostatically. Then carbon nuclei react with one another (^{12}C + ^{12}C) to form mainly Ne, Na and Mg. If the star is massive enough, the carbon burning stage will be followed by Ne-photodisintegration which mainly transforms Ne into oxygen which then can be ignited itself to undergo $^{16}O + {}^{16}O$ fusion [92].

$$
\begin{array}{lll}
^{12}C + {}^{12}C & & ^{24}Mg + \gamma + 13.930\ \text{MeV} \\
 & & ^{23}Na + p + 2.238\ \text{MeV} \\
 & & ^{20}Ne + {}^{4}He + 4.616\ \text{MeV} \\
 & & ^{23}Mg + n - 2.605\ \text{MeV} \\
 & \longrightarrow & ^{16}O + 2\,{}^{4}He - 0.114\ \text{MeV}
\end{array}
$$

At a temperature $\approx 2 \times 10^{9}$K, oxygen will also react with itself according to the reactions.

$$
\begin{array}{llll}
^{16}O + {}^{16}O & & ^{32}S + \gamma & + 16.539\ \text{MeV} \\
 & & ^{31}P + p & + 7.676\ \text{MeV} \\
 & \longrightarrow & ^{31}S + n & + 1.459\ \text{MeV} \\
 & \longrightarrow & ^{28}Si + {}^{4}He & + 9.593\ \text{MeV} \\
 & \longrightarrow & ^{24}Mg + 2\,{}^{4}He & - 0.393\ \text{MeV}
\end{array}
$$

During central *C*-burning, the neutron capture nucleosynthesis develops upon the seed nuclei left by the previous core He burning since He core is convective, the initial abundances are uniform throughout the core at *C*-ignition. The neutrons in the *C*-burning core of massive stars are essentially produced by $^{22}Ne\ (\alpha, n)\ ^{25}Mg$ and corresponding fluxes calculated by Arcoragi *et al* [93], are shown in Figures 12 and 13. Their obtained result may

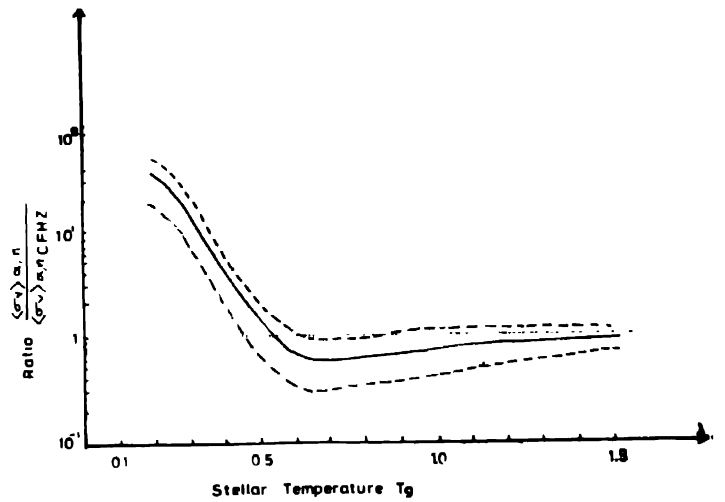

Figure 11. Reaction rate $^{22}Ne\ (\alpha, n)\ ^{25}Mg$ normalized to CFHZ value with the assumption that the 623 KeV resonance could be ascribed to $^{22}Ne\ (\alpha, n)\ ^{25}Mg$.

appear somewhat surprising in the light of the analysis by Arnett and Thielemann [94], who identify $^{13}C\ (\alpha, n)\ ^{16}O$ as the dominant neutron producer in the relevant conditions. However, they also found that for $T > 8 \times 10^{8}$K, $^{21}Ne\ (\alpha, n)\ ^{24}Mg$ can be an as efficient neutron producer as $^{22}Ne\ (\alpha, n)\ ^{25}Mg$ at one point or another in the evolution of some of the *C*-burning layers. They also showed that the last potentially important neutron source ^{25}Mg (α, n) ^{28}Si is by far the least effective.

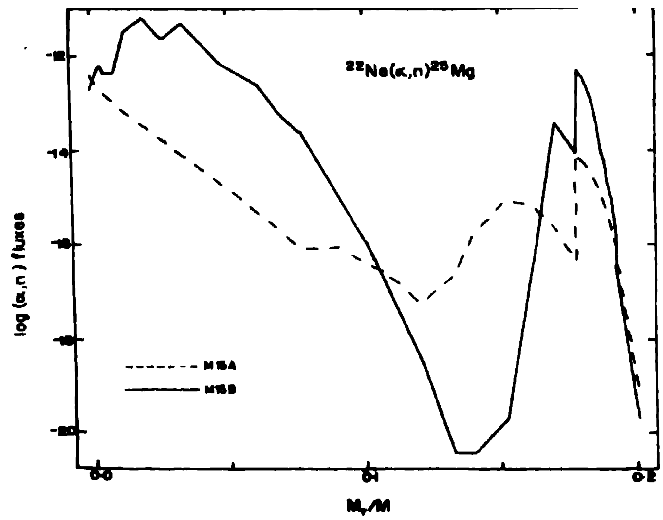

Figure 12. Nuclear fluxes corresponding to ^{22}Ne (α, *n*) ^{25}Mg *vs* the mass coordinate M_r/M for the star of mass 15·M. Model M 15A corresponds to the contraction phase toward C-ignition, while model M 15B relate to Central C exhaustion. These fluxes are defined as $\rho X_4 X_i$, $N_A < \sigma v >$where X_4, Xi are the mass fraction of α particles and of ^{13}C, ^{21}Ne or ^{22}Ne, while $N_A < \sigma v >$ designates the relevant (α, *n*) rate in usual notation.

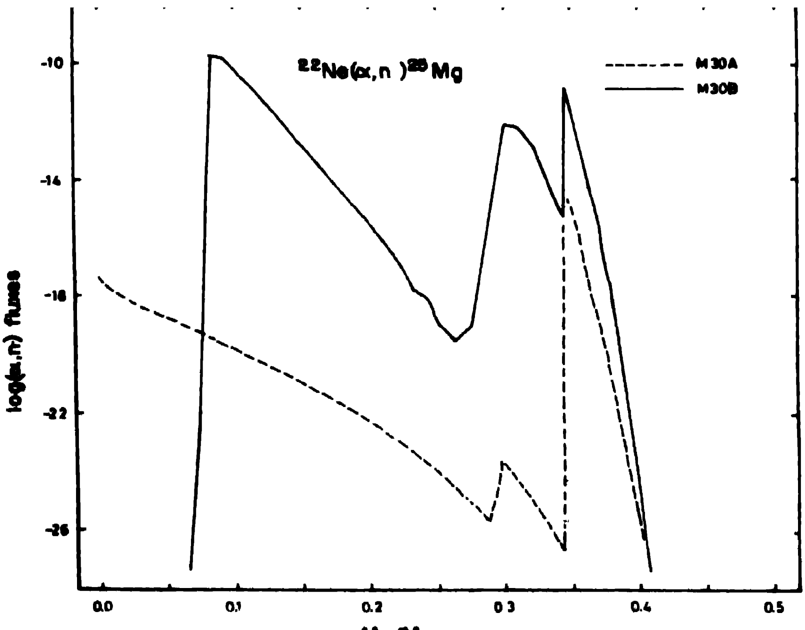

Figure 13. Nuclear fluxes corresponding to ^{22}Ne (α, n) ^{25}Mg *vs* the mass coordinate M_r/M for the star of mass 30M. Notations are same as in Figure 12. The neutrons in the C-burning core of model M15 and M30 (Mr/M $\leq$ 0·05 and 0·1 respectively) are essentially produced by ^{22}Ne (α. n) 25

4.5. Silicon burning :

At the end of Carbon and oxygen burning, the most abundant nuclei will be ^{32}S and ^{28}Si with significant amount of ^{24}Mg. Because the binding energies for protons, neutrons and alpha particles in ^{32}S are smaller than those in ^{28}Si, the nuclei ^{32}S will be the first to photo-disintegrate according to the reactions :

$$^{32}S + \gamma \longrightarrow {}^{31}P + p - 8.864 \text{ MeV}$$

$$^{31}P + \gamma \longrightarrow {}^{30}Si + p - 7.287 \text{ MeV}$$

$$^{30}Si + \gamma \longrightarrow {}^{29}Si + n$$

$$^{29}Si + \gamma \longrightarrow {}^{28}Si + n$$

The resulting reactions will leave a little amount of ^{28}Si. Most nuclear species between ^{28}Si and ^{59}Co (except neutron rich species ^{36}S, ^{40}Ar, ^{43}Ca, ^{48}Ca, ^{51}Ti, ^{54}Cr, ^{58}Fe) are generated by a quasi equilibrium processes in which the only important thermonuclear reaction rates are thought to be those of the bottleneck nuclei ^{44}Ca, ^{45}Sc, ^{45}Ti.

5. Supernova stage

Towards the end of the Si burning process, the core of the star has reached a temperature in excess of 10^9K and iron group nuclei are available. These heavy elements are known as products of stellar deaths [95]. When a massive star has reached the end of its nuclear fuel, it can become a supernova. Thus a supernova arises when the core of a star collapses under its own gravitational contraction releasing energy which causes the outer envelope to explode i.e. the inner part of a star undergoes an implosion, while the outer part undergoes an explosion. The imploding core may form a white dwarf or neutron star depending upon the type of supernovae.

Type I supernovae may be the ultimate fate for a narrow range of intermediate mass stars (6M. ≤ M≤ 8M.) which initiates carbon burning under electron degenerate condition. The runaway thermonuclear carbon burning may be enough to explode the star leaving no remnant [96,97]. While type II supernovae may be the end result for massive (M ≥ 10M.) stars [98-101].

Just prior to collapse, the core of the star largely consists of ^{54}Fe and neutron-rich isotopes such as ^{48}Ca, ^{50}Ti, ^{54}Cr and ^{58}Fe, which are ashes of the silicon-burning shell. Outer layers include the ashes from the oxygen, neon, carbon, helium and hydrogen burning shells. In the case of supernova explosion, the temperature becomes so high ($T > 4$–5×10^9K) during a short time scale ($\tau \sim 1$ sec) that many nuclear reactions do occur and usually transform the final abundances of the ejected mass. Thus, the explosion of supernova does not only lead to a strong outburst of energy but also to the formation of a remnant which remains energetic for a rather longtime 10^4 to 10^5 years [102]. The remaining star becomes a neutron star *i.e.* a source of a pulsar phenomena.

The hypothetical mechanism which trigger the supernovae explosion are : (i) Fe-photodisintegration, (ii) *C* detonation, (iii) the neutrino transport, (iv) rotational energy transfer from the central pulsar. Out of all the possible mechanism Fe-photodisintegration is the most remarkable.

Fe-photodisintegration:

The temperature in the central region in the case of massive star (>8 M.) is $T \geq 5 \times 10^9$K and at such temperatures photo-disintegration can take place.

$$Fe + \gamma \leftrightarrows 13\,{}^4He + 4n$$

The reaction is highly endo-energetic (as ^{56}Fe nucleus is very stable) and may induce a violent collapse of the central region of the star. The implosion of Fe core is rapidly followed by the explosion of the matter which has not yet finished its nucleosynthetic evolution. In the same time, the core of Fe can be neutronized i.e. the protons in the nuclei can capture electrons and be transformed into neutrons. The central part of the supernova then becomes a neutron star.

6. Neutron star stage

As the central density increases for a given composition the electron fermi energy always increases upto the point where inverse beta decay takes place and drives the electrons into the nuclei. This is what produces the increasingly neutron rich elements ^{32}S, ^{56}Fe, ^{120}Sn, etc. The symbolic reaction is

$$p + e^- \qquad n + \nu$$

The reverse reaction cannot take place if the fermi energy is high enough, because all the electron states into which radioactive nucleus might decay, are already occupied. This gives an otherwise unstable nuclei an environmentally induced stability. During contraction, the value of effective nuclear mass per free electron also increases. When the fermi energy reaches 24 MeV, the density is $10^{11.5}$ g. cm^{-3}. At this stage free neutrons become energetically favourable so that a further increase in density leads to an increased partial density of neutrons, a practically constant density of ions and a constant electron fermi energy of 24 MeV. As the density increases, the reaction ($p + e \longrightarrow n + \nu$) proceeds rapidly and the electrons are driven into the nuclei causing the collapse of the central core, because the electron pressure no longer increases at a sufficient rate during the contraction. The core of massive neutron stars probably contain a variety of mesons, baryons and hyperons, in addition to the neutrons [42,102]. At these very high densities general relativistic effects must also be taken into consideration. The region is of greatest importance because potentially it is in these last stage that a star can give off by far its greatest amount of energy by converting a large fraction of its mass into some form of radiation, perhaps gravitational.

7. Conclusion

Various neutron sources have been placed only on time scale (as snown in Figure 14). From the figure it is seen that at high temperature helium burning reactions produce neutrons. These neutrons are then thermalized and rapidly captured by iron group nuclei. At high density regiôn neutronization takes place and in nuclear statistical equilibrium it consists of heavy neutron rich elements and large number of free neutrons.

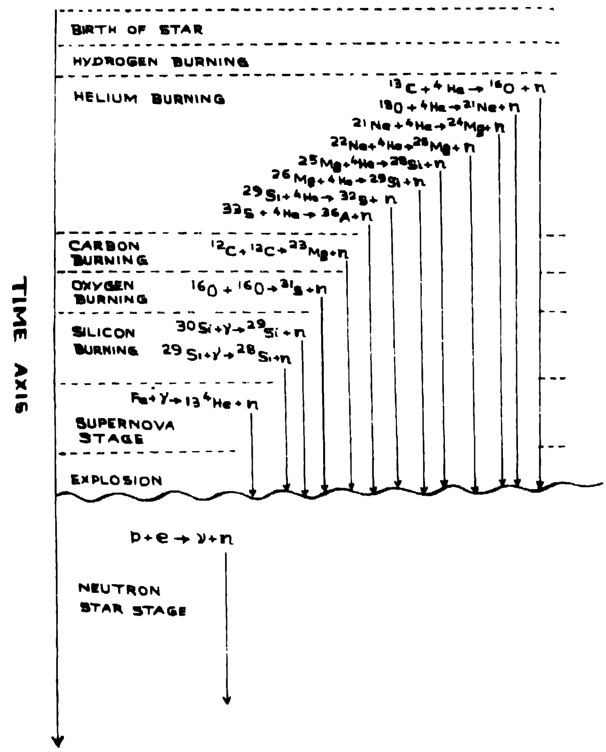

Figure 14. Schematic diagram of only neutron sources placed on time axis. The time axis is not drawn to scale. Arrows indicate neutron paths through next stages. The wavy line marks the moment when the star loses stability whereupon its central parts collapse to form a neutron star and the envelope is expelled

Acknowledgment

The author wishes to thank Professor H N K Sarma for constant encouragement. He is very thankful to the anonymous referee for his critical comments in improving the quality of this paper. The author gratefully acknowledges the help of Prof D L Lambert, Prof T Tatsumi, Ju L Frantsman through the reprints of their own works and of Mrs Tapati Parui and Manabendra Parui in the preparation of this manuscript.

References

[1] G Gamow 1938 *Phys. Rev* **54** 480

[2] H A Bethe 1939 *Phys. Rev.* **55** 103, 434

[3] P W Merrill 1947 *Astrophys. J.* **105** 360

[4] P W Merrill 1952 *Science.* **115** 484

[5] L H Aller and P C Keenen 1951 *Astrophys. J.* **113** 72

[6] W Buscombe and P W Merrill 1952 *Astrophys. J.* **116** 525

[7] W P Bidelman 1953 *Astrophys. J* **117** 377

[8] P W Merrill and J L Greenstein 1956 *Astrophys. J. Supl.* **2** 225

[9] R G Teske 1956 *Publ. Astron Socy Paci.* **68** 520

[10] F Hoyle, W A Fowler, G R Burbidge and E M Burbidge 1956 *Science* **124** 611

[11] G M Burbidge, E M Burbidge, W A Fowler and F Hoyle 1957 (B^2HF) *Rev. Mod. Phys.* **29** 547

[12] A G W Cameron 1957 *Chalk River Rep* CRL **41**

[13] J V Narlikar 1978 *The Structure of the Universe* (UK . Oxford University Press)

[14] R Jastrow, M H Thompson 1984 *Astron. Fundamental & Frontiers* (New York: John Wiley) p 191

[15] V M Goldschmidt 1937 *Skr Nor Vidensk Acad. Oslo* **1**, no 4

[16] H N Russell, W S Adams, 1928 *Astrophys. J.* **68**, 9

[17] A Unsold 1979 *Les Elements et leurs Isotopes dans l'Univers* (Liege : Univ. of Liege) p 7

[18] F Kappeler, H Beer and K Wisshak 1989 *Rep Prog Phys* **52** 945

[19] R A Alpher 1948 *Phys. Rev* **74** 1577

[20] R A Alpher, H Bethe and G Gamow 1948 *Phys Rev.* **73** 803

[21] R V Wagoner, W A Fowler and F Hoyle 1967 *Astrophys J* **148** 3

[22] R V Wagoner 1973 *Astrophys J.* **179** 343

[23] D N Schramm R V Wagoner 1977 *Ann Rev. Nucl Sci.* **27** 37

[24] P W Merrill 1952 Ref. **4** p 485

[25] P W Merrill, 1947 Ref. **3** p 360

[26] P W Merrill and J L Greenstein 1956 Ref. **8** p 225

[27] L H Aller and P C Keenen 1951 *Astrophys J* **113** 72

[28] W Buscombe and P W Merrill 1952 Ref. **6** p 525

[29] W P Bidelman 1953 *Astrophys. J.* **117** 377

[30] R. G. Teske 1956 *Publ. Astron Socy Pacific* **68** 520

[31] S E Woosley and W M Howard 1978 *Astrophys J Suppl* **36** 285

[32] G R Burbidge, E M Burbidge, R F Christy and W A Fowler 1956 *Phys. Rev.* **103** 1145

[33] W Baade, G R Burbidgege, F Hoyle, R F Christy and W A Fowler 1956 *Publ. Astron. Socy Pacific* **68** 296

[34] F Hoyle, W A Fowler, G R Burbidge and E. M Burbidge 1957 *Science* **124** 611

[35] G R Burbidge, E M Burbidge, W A Fowler and F Hoyle 1957 *Rev. Mod Phys* **29** 547

[36] A G W Cameron 1957 *Chalk River Rep* CRL **41**

[37] E Anders, M Ebihara 1982 *Geochim Cosmochem.* **46** 2263

[38] A G W Cameron 1982 *Essays in Nuclear Astrophys* eds. Barnes *et al* (Cambridge, UK: Cambridge Univ. Press)

[39] A G W Cameron 1955 *Astrophys. J.* **121** 144

[40] H Reeves 1966 *Astrophys. J.* **146** 447

[41] A G W Cameron 1960 *Astron J.* **65** 485

[42] H Reeves 1968 *Stellar Evolution and Nucleosynthesis* (New York : Gordon & Breach)

[43] W D Arnett and F K Thielemann 1984 *Astrophys. J.* (preprint)

[44] B J Allen , J H Gibbon and R L Macklin 1971 *Adv. Nucl. Phys.* **4** 205

[45] A G W Cameron, M D Delano and J W Truran 1970 *CERN* **70-30** 735

[46] W Hillebrandt and F K Thielemann 1977 *Astron. Astrophys* **52** 63

[47] J W Truran, J J Cowan, A G W Cameron 1978 *Astrophys. J.* **222** L63

[48] J W Truran 1978 *Int. Symp Superheavy Elements* eds Lodai, MAK (Oxford : Perganon) p 515

[49] J B Blake, S E Woosley, T A Weaver and D N Schramm 1981 *Astrophys. J.* **248** 315

[50] W Hillebrandt 1982 *Astron. Astrophys.* **110** L3

[51] W Hillebrandt, K Nomoto and R G Wolf 1984 *Astron. Astrophys.* **133** (preprint)

[52] D N Schramm 1982 Ref. 38. p 325

[53] J W Truran 1987 Ref. 48 p 515

[54] G J Mathews, S D Bloom and R F Hansman 1983 *Phys. Rev.* **C28** 1367

[55] G J Mathews, A Mengoni, F K Thielemann and W A Fowler 1983 *Astrophys. J.* **270** 740

[56] T Lee, D N Schramm, J P Wefel and J B Blake 1979 *Astrophys. J* **232** 854

[57] R Giacconi and R Ruffini 1978 *Proc Intl School Phys , Enrico Fermi, Course LXV* (Amsterdam: North Holland)

[58] H Reeves 1968 Ref. 42 p 75

[59] E E Salpeter 1952 *Astrophys J* **115** 326

[60] E E Salpeter 1953 *Ann Rev Nucl Sci* **2** 41

[61] E J Opik 1951 *Proc. Roy Irish. Acad* **A54** 49

[62] E J Opik 1954 *Mem Soc Roy. Sci Liege.* **14** 131

[63] F Hoyle and M Schwarzschild 1955 *Astrophys J Supl.* **2** 1

[64] F Kappeler, H Beer and K Wisshak 1989 *Rep. Prog Phys* **52** 945

[65] J Audouze and V Vonclair 1980 *Ref* 70 Ch. Nucleosynthesis

[66] H A Bethe, 1982 Ref. 38 p 439

[67] C A Von Weizsacker 1938 *Z Phys.* **39** 633

[68] J L Greenstein 1954 *Modern Physics for Engineers* (New York · McGraw Hill) p 267

[69] A G W Cameron 1954 *Phys Rev* **93** 932

[70] W A Fowler, G R Burbidge and E M Burbidge 1955 *Astrophys J* **122** 271

[71] K R Lang 1980 *Astrophys Formulae* (Heidelberg · Springer-Verlag)

[72] J Audouze and V Vonclair 1980 *An Introduction to Nucl. Astrophys* (Holland . D Riedel)

[73] R K Ulrich 1982 Ref 37 p 301

[74] I Iben 1975 *Astrophys J* **196** 525, 549

[75] K Wolke, C Rolfs, H P Trautvetter, V Harms, M Wiescher, K L Kartz and J W Hammer 1989 *Proc 5th Workshop on Nucl Astrophys. MPA/P1* (Max Planck Institute, Garching, Germany) p 1

[76] G R Caughlan, W A Fowler, M J Harris and B A Zimmerman 1985 *At Data Nucl. Data Tables* **32** 197

[77] N Prantzos, M Amould and J P Arcoragi 1987 *Astrophys J* **315** 209

[78] M Busso, G Picchio, R Gallino and A Chieffi 1988 *Astrophys J* **326** 196

[79] H Beer, G Rupp, F Voss and F Kappeler 1989 Ref 75 p 6

[80] H W Drotleff, A Denker, J W Hammer, H Knee, S Kuchler, C Rolfs, D Streit and H P Trautvetter 1990 *Proc Int Symp Nucl Astrophys MPA/P4* (Max Planck Institute, Garching), p 181

[81] P Descouvemont 1987 *Phys Rev.* **C36** 2206

[82] K Wolke, V Harms, H W Becker, J W Hammer, K L Kartz, C Rolfs, U Schroder, H P Trautvetter, M Wiescher and A Wohr 1989 *Z Phys* **A334** 491

[83] B L Berman, R L Van Hemert and C D Bowman 1969 *Phys Rev Lett* **23** 386

[84] C M Raiten, M Busso, R Gallino and G Picchio 1990 Ref 80 p 281

[85] H W Drotleff, A Denker, J W Hammer, H Knee, S Kuchler and D Streit 1991 *Proc. Intl Workshop Nucl Astrophys MPA/P5.* (Max.Planck Institute, Garching) p 23

[86] H Wiegmann, R L Macklin and J A Harvey 1976 *Phys. Rev* **C14** 1328

[87] W E Bennett, P A Roys and B J Toppel 1954 *Phys Rev* **C14** 924

[88] C N David 1968 *Nucl. Phys.* A110 619

[89] T R Wang, R B Vogelaar and Kavangh 1991 *Phys. Rev.* C43 (preprint)

[90] J V Narlikar 1978 Ref. 13 p 47

[91] G J Mathews and R A Ward 1985 *Rep. Prog. Phys.* 48 1371

[92] E Kolbe, K Langanke and F K Thielemann 1990 Ref. 80 p 195

[93] J P Accoragi, N Langer and M Arnould 1990 *Max Planck Inst. Graching, Preprint no· MPA* 559

[94] W D Arnett and F K Thielemann 1985 *Astrophys. J.* 295 589

[95] J Audouze and V Vauclair 1980 Ref. 70 p 61

[96] W B Arnett 1975 Ref. 57 p 356

[97] F Hoyle and W A Fowler 1960 *Astrophys. J.* 132 565

[98] W D Arnett 1977 *Astrophys J.* 218 815

[99] J C Wheeler 1981 *Rep. Prog. Phys.* 44 85

[100] H A Bethe 1982 Ref. 38 p 439

[101] S E Woosley and T Weaver 1982 Ref. 38 p 377

[102] J Audouze and V Vauclair, 1980 Ref. 70 p 64

About the Reviewer

Ramen Kumar Parui is at present in the Physics Department of Manipur University. His degrees came from Calcutta University (BSc), Manipur University (MSc), PhD (will be declared). He is interested in the physics of Neutron Stars. At present, he is working on the behaviour of the neutron star's internal magnetic field and its role towards gravitatoinal wave source, and related area like magnetic monopoles.